Two-Dimensional Finite Difference Time Domain (FD-TD) Model of Electromagnetic (EM) Scattering From a Buried Rectangular Object

Thomas A. Korjack

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REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 1995	3. REPORT TYPE AND DATES COVERED Final, June 1993–June 1994

4. TITLE AND SUBTITLE

Two-Dimensional Finite Difference Time Domain (FD-TD) Model of Electromagnetic (EM) Scattering From a Buried Rectangular Object

5. FUNDING NUMBERS

4B592502354010

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-713

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A two-dimensional transverse-magnetic (TM) electromagnetic (EM) scattering problem from buried dielectric objects due to a Gaussian pulse is numerically solved using the Finite Difference Time Domain (FD-TD) method with absorbing boundary conditions via Maxwell's equations. The scatterers are rectangular cross sections in a multilayer media; the Gaussian pulse is reflected into a lossy "earth" by a finite, 45° plate that is part of the detector that receives the EM signal.

Spatial distributions of electric field components are calculated over time for single and multiple land scatterers (mines). The scattered fields gradually diminish with time and are then eventually dissipated. Carpet plots are illustrated to depict the spatial distributions of the scattered field component at comparative time steps for one, two, and three distinct scatterers or land mines within the lossy media. Results clearly illustrate the typical wave patterns expected under the simulated conditions as presented in this report — i.e., conductivity (s) for the air is 0, conductivity for the earth is 0.01, conductivity for the grass is 0.005, and conductivity for the mines are 0, 0.02, and 0.008; permeability (V • s/A • m) values ranged from 1 for air, 9 for earth, 5.5 for grass, and 2.3, 5.6, and 23.0 for the mines, respectively. Numerical analysis indicates that the difference of scattered signals between single and multiple scatterers are considerably obvious from the point of view of both time domain and frequency domain.

14. SUBJECT TERMS

finite difference theory, time domain, electromagnetic scattering

15. NUMBER OF PAGES
29

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
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1. INTRODUCTION

This analysis entails the two-dimensional (2-D) time-dependent transverse-magnetic (TM) electromagnetic (EM) scattering of dielectric objects of rectangular cross sections buried in a multilayer lossy medium (grass and earth). The incident field is a Gaussian pulse which is reflected into the grass and earth by one side of the detector situated 45° with respect to the earth-grass interface. As the Gaussian pulse is spread into the earth, it encounters the buried objects and is reflected and scattered. The scattered fields are detected by sensors at the bottom and other side of the detector (see Figure 1). Frequency domain characteristics for the scattered signal can be obtained by Fourier transformation of the time-dependent signal. The intent of this study is to generically analyze a 2-D high-frequency scattering problem dealing with multimedia using absorbing boundary conditions (ABC) which can serve as a starting point for a three-dimensional (3-D) case involving the same phenomena with additional computational requirements necessitating the utilization of parallelization on a variety of parallel architectures. This effort is not designed to exhaust all EM variations of detectors, sensors, and multimedia applications nor to deal with land mine technology per se, but instead to capitalize on the development of Maxwell's equations to generate wave distributions and effects in a very general sense; specific applications can be generated and interpreted based upon post-processing of the data produced by the numerical scheme.

Generally, there are two time domain methods for solving EM scattering problems, i.e., the time-domain finite-element (TD-FE) method suggested and studied by the group at the University of California at Berkeley [1–4] and developed by Lee and Madsen [5], and the finite-difference time-domain (FD-TD) method suggested by Yee in 1966 [8] and developed by many authors [9–37]. The TD-FE method has been primarily used for the scattering of buried objects especially where there is a simple medium, a single scatterer, and a simply shaped detector [3,4]. The solution methodology is restricted since the decomposition of the position of calculated field values into direct and reflected components is not easy to complete for the multireflection case caused by multilayer media, multiple scatterers, or complex detector configurations. Moreover, the FD-TD method can be applied to problems with complex structures which are very difficult to solve with either analytical or other numerical methods. Hence, the FD-TD method is suitable for solving EM scatterings that occur in multilayer media, multiple scatterers, and complex detector configurations.
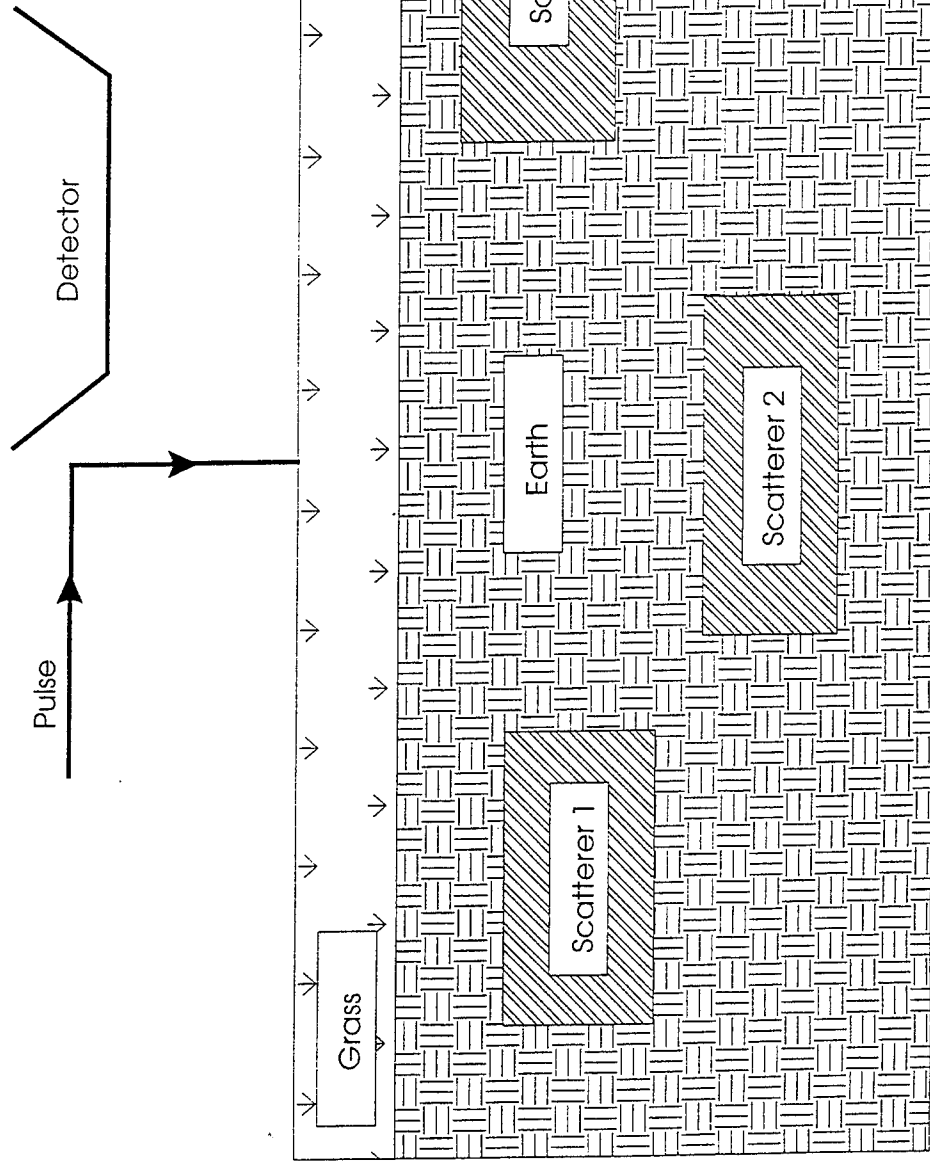
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Figure 1. Topology of scattering phenomena.

The problem just described is solved using the FD-TD method which has been implemented by means of a simple FORTRAN program for numerical computations as done similarly by Mei [6] with the notable exception that the solution methodology executed herein invokes a fractional step difference scheme as demonstrated by Shang [7]. The scattered fields of buried rectangular dielectric objects, due to an incident field composed of a reflected Gaussian pulse, can be effectively computed within reason.

In section 2, the mathematical and numerical background of the FD-TD approach is reviewed for the simple case of 2-D TM excitation. Issues such as discretization of Maxwell's equations for lossy media, stability, simulation of ABC, scattered field formulation, and Gaussian pulse properties are also discussed. The computer program simulates damping- and super-ABC, and the formation of a reflected Gaussian pulse; a more detailed treatment of the boundary conditions and pulse generation should be consulted in the references.

2. LITERATURE REVIEW

The FD-TD method proposed by Yee [8] is based on the direct solution of the time-dependent Maxwell's curl equations such that the central difference approximations are applied to both space and time derivatives in the respective equations. Knowing the initial, boundary, and source conditions, the resulting discretized equations are solved using a leap-frog time-marching procedure. EM wave propagation and interactions are thus numerically simulated. In subsections 2.1–2.6, the details of the algorithm are described.

2.1 <u>Difference Equations and Node Distribution</u>. The Maxwell's equations governing the propagation of EM waves in an isotropic, homogeneous medium are as follows [3]:

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu} \nabla \times \vec{E} \qquad (1)$$

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\varepsilon} \left[\nabla \times \vec{H} - \sigma \vec{E} \right], \qquad (2)$$

where μ (permeability), ε (permittivity), and σ (conductivity) may be functions of space.

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For 2-D TM scattering problems, we may adapt a spatial lattice defined on a rectangular (x, y) coordinate system. Equations (1) and (2) can then be written in x-y component form as follows [3,4]:

$$\varepsilon \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z \tag{3}$$

$$\mu \frac{\partial H_x}{\partial t} = - \frac{\partial E_z}{\partial y} \tag{4}$$

$$\mu \frac{\partial H_y}{\partial t} = \frac{\partial E_z}{\partial x} \tag{5}$$

If an inhomogeneous medium with continuous variation of material constants was considered, then ε, μ, and σ would have to be specified at each particular grid point. However, for a heterogeneous medium where step changes of material constants occur at interfaces, equations (3)–(5) will need to be modified to account for these spatial variations. If the magnetic component H_x is normal to the interface for the TM case, such modifications can be avoided.

2.2 Stability Condition. In order for the numerical solution to be stable, the following Courant stability condition must be satisfied:

$$V_m \Delta t \leq \frac{1}{\sqrt{\left(\frac{1}{\Delta x}\right)^2 + \left(\frac{1}{\Delta y}\right)^2 + \left(\frac{1}{\Delta z}\right)^2}}, \tag{6}$$

where V_m is the velocity of light in the medium. When $\Delta x = \Delta y = \Delta z = \Delta h$, equation (6) reduces to

$$V_m \Delta t \leq \frac{\Delta h}{\sqrt{3}}. \tag{7}$$

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For the 2-D case, the stability condition becomes

$$V_m \Delta t \leq \frac{\Delta h}{\sqrt{2}}.$$

(8)

It should be noted that V_m takes on the maximum velocity value in the case of a multimaterial problem.

2.3 Scattered Field Formulation. For an EM scattering problem, the total electric field can be decomposed into incident and scattered fields, i.e.,

$$\vec{E}^{tot} = \vec{E}^{inc} + \vec{E}^{sc},$$

(9)

where the incident field $\vec{E}^{inc}$ is defined to be the field which exists in the absence of the scatterer. Therefore, the scattered field becomes

$$\vec{E}^{sc} = \vec{E}^{tot} - \vec{E}^{inc}.$$

(10)

Once the total and incident fields are found, the scattered field can be obtained.

2.4 Absorbing Boundary Conditions (ABC). There are several ways to approximate ABC for use in numerical simulations; Fang's Ph.D. dissertation [21] gives a very good explanation and account of these. Two particular implementations developed by Mei and Fang [12] will be discussed here, i.e., super-ABC [21] and damping ABC [22].

2.4.1 Super-ABC. Let us define a constant s such that

$$s = \frac{c}{\Delta h},$$

where c is the speed of light in free space.

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The time it takes an EM wave to transit one grid spacing in a medium with wave speed V_m is

$$t = \frac{\Delta h}{V_m}.$$

In the numerical approximation, we chose s for convenience so that the wave transits one grid spacing in an integer number, m, of time steps Δt, and require that Δt satisfy the Courant stability criterion, i.e., equation (8). Therefore,

$$\frac{t}{\Delta t} = m, \tag{11}$$

where m is an integer.

The super-ABC is implemented in the following manner. First, the tangential electric field vectors $\vec{E}_t$ at each boundary point are set equal to the corresponding vector value one space step forward in the direction of propagation and m time steps earlier, where m is determined by equation (11). Secondly, this same procedure is applied to the tangential magnetic field vector s $\vec{H}_t$ at each boundary point. Third, $\vec{H}_t$ is calculated using the FD-TD method. Finally, the super-ABC is then summated using a weighted average of two $\vec{H}_t$ values; one used is $\vec{H}_t$ (shifted) obtained by shifting $\vec{H}_t$ in m time steps earlier to one space step forward, and another is $\vec{H}_t$ (FD-TD) calculated directly by the FD-TD method. Thus,

$$\vec{H}_t \text{(super-absorbing)} = \frac{\vec{H}_t \text{(TD - FD)} + m\vec{H}_t \text{(shifted)}}{(m + 1)}. \tag{12}$$

2.4.2 Damping ABC. The basic idea of the damping ABC is to locate damping layers with proper electric and magnetic loss characteristics just inside the physical boundaries. The loss coefficient is zero at the inside of the damping layers but increases toward the outer boundary. The incident EM energy will then be absorbed in these damping layers with little reflection. The appropriate scheme for implementation in the FD-TD method is as follows [22]:

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$$\vec{E}^{n+1} = (1 - \Delta t \gamma) \vec{E}_I^{n+1} \tag{13}$$

$$\vec{H}^{n+\frac{1}{2}} = (1 - \Delta t \gamma) \vec{H}_I^{n+\frac{1}{2}}, \tag{14}$$

where the field values for $\vec{E}_I$ and $\vec{H}_I$ are obtained by the original FD-TD scheme with $\gamma = 0$. The damping ABC is thus implemented by multiplying the fields $\vec{E}_I$ and $\vec{H}_I$ by $(1 - \Delta t \gamma)$ as indicated in equations (13)–(14). Different functional forms of $(1 - \Delta t \gamma)$ result in different absorbing effects, e.g., the case where a functional form like $e^{-\alpha z^2}$ is adopted.

This report considers the combination of both ABCs. Using this mixed boundary treatment, together with a large enough computation domain, an accurate time-domain scattered field can be obtained which can be used in the following Fourier transformation.

2.5 Gaussian Pulse. The excitation pulse used is Gaussian in shape, which has a smooth time dependence. Its Fourier transform (spectrum) is also a Gaussian pulse centered at zero frequency. These useful properties make this pulse shape a good choice for investigating the frequency-dependent characteristics of the EM scattering from a buried object via Fourier transformation of the response to the scattered pulse [19].

A Gaussian pulse, g(t,x), propagating in the +x direction in a given medium can be represented as the following [19,20]:

$$g(t,x) = \exp\left[\frac{\left((t - t_0) - \dfrac{x - x_0}{V_m}\right)^2}{T^2}\right], \tag{15}$$

where V_m is the speed of the pulse in the specific medium and T is the period. The pulse has its maximum at (x_0, t_0).

The Fourier transform, G(f), of g(t,x) has the form,

$$G(f) \propto \exp\left[-\pi^2 T^2 f^2\right].$$

(16)

The choices for the parameters T, t_0, and x_0 are dependent upon the following two requirements:

• Requirement 1: For $\Delta h \leq$ the smallest characteristic dimension of the structure and Δt satisfying the Courant stability criterion, the Gaussian pulse must span a sufficient distance for adequate resolution of the wave patterns, and (2) The spectrum of the pulse must be wide enough (or the pulse must be narrow enough) to maintain a substantial value within the high frequency range of interest (i.e., 200–1,500 MHz).

The pulse width W is defined as the distance between the two symmetric points on the pulse (curve) corresponding to 5% of the maximum pulse amplitude. Therefore, T (the period) can be determined from the following [19]:

$$\exp\left[-\frac{\left(\dfrac{W}{2}\right)^2}{(V_m T)_2}\right] = \exp(-3) \qquad (\approx 5\%),$$

(17)

or after rearranging terms,

$$T = \left(\frac{1}{\sqrt{3}}\right)\left(\frac{\dfrac{W}{2}}{V_m}\right).$$

(18)

The maximum frequency f_{max} then becomes

$$f_{max} = \frac{1}{2T} \qquad [G\left(\frac{1}{2T}\right) \approx 0.1\,]$$

$$= \frac{\sqrt{3}\, V_m}{W}.$$

(19)

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• Requirement 2: The choice for x_0 and t_0 must be made such that the initial energization of the excitation will be small and smooth. Although using the Gaussian pulse as the excitation source significantly reduces the necessary amount of characteristic frequency computations, the Fourier transform of the fields is very sensitive to time domain errors, especially to imperfect ABC errors.

2.6 Fourier Transform. The time domain signals received by sensors can be transformed to the frequency domain signals as follows:

$$E_z^s(\omega) = \int_0^\infty E_z^s(t) \exp(-j\omega t)\, dt , \tag{20}$$

where $\omega = 2\pi f$.

After making the substitution $\omega = 2\pi f$ and casting the right-hand side of equation (20) in discretized form, we have

$$E_z^s(f) = \sum_{n=1}^N E_z^n \exp(-j2\pi f n \Delta t) , \tag{21}$$

where N = maximum number of time steps.

3. RESULTS

Two-dimensional TM EM scattering from buried dielectric objects due to a Gaussian pulse is numerically solved using the FD-TD method with ABC. The scatterers are rectangular cross sections in a multilayer media; the Gaussian pulse is reflected into a lossy "earth" by a finite, 45° plate. This plate is the part of a detector that receives the EM signal. All of the results match very favorably with Mei [6] notwithstanding the utilization of the fractional step finite difference scheme.

Figures 2–4 represent the spatial distributions of scattered field component $E_z^s(x,y)$ at certain time steps for just a single land mine. The scattered field gradually diminishes and is then eventually dissipated with increasing time steps as expected. Figures 5–10 also represent the spatial distributions of the scattered field component at comparative time steps for both two and three distinct scatterers or land mines within the lossy media. All carpet diagrams clearly illustrate the typical wave patterns expected under the

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2-D Scattering of a Buried Rectangular Object

Time Step: 330

Ez

X

Y

Figure 2. Distribution of electric field intensity (V/m) for one scatterer vs. X (5.0×10^{-3} m) and Y (5.0×10^{-3} m), time step - 330.

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2-D Scattering of a Buried Rectangular Object

Time Step: 530

Figure 3. Distribution of electric field intensity (V/m) for one scatterer vs. X (5.0×10^{-3} m) and Y (5.0×10^{-3} m), time step - 530.

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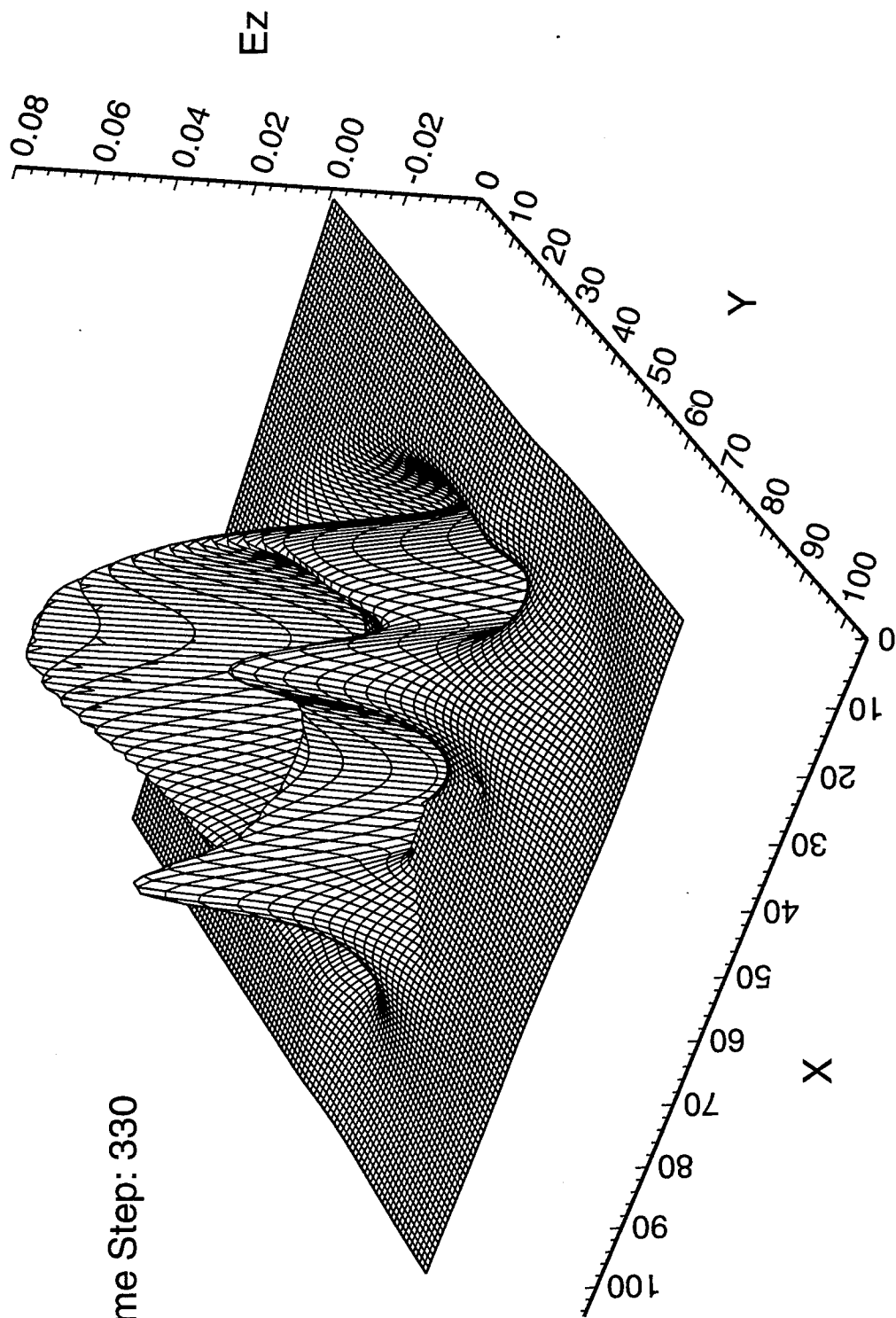2-D Scattering of a Buried Rectangular Object
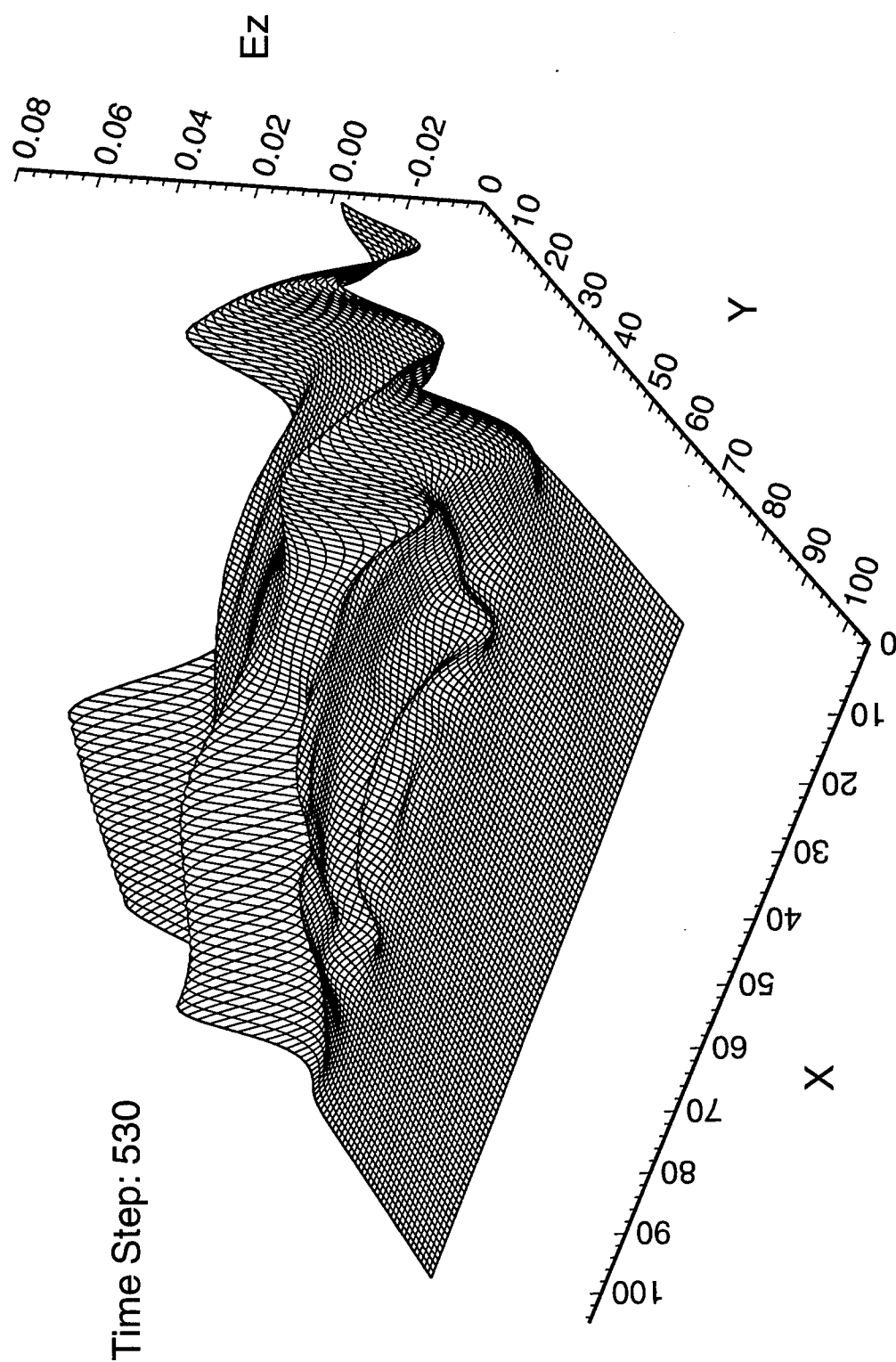
Time Step: 800

Ez
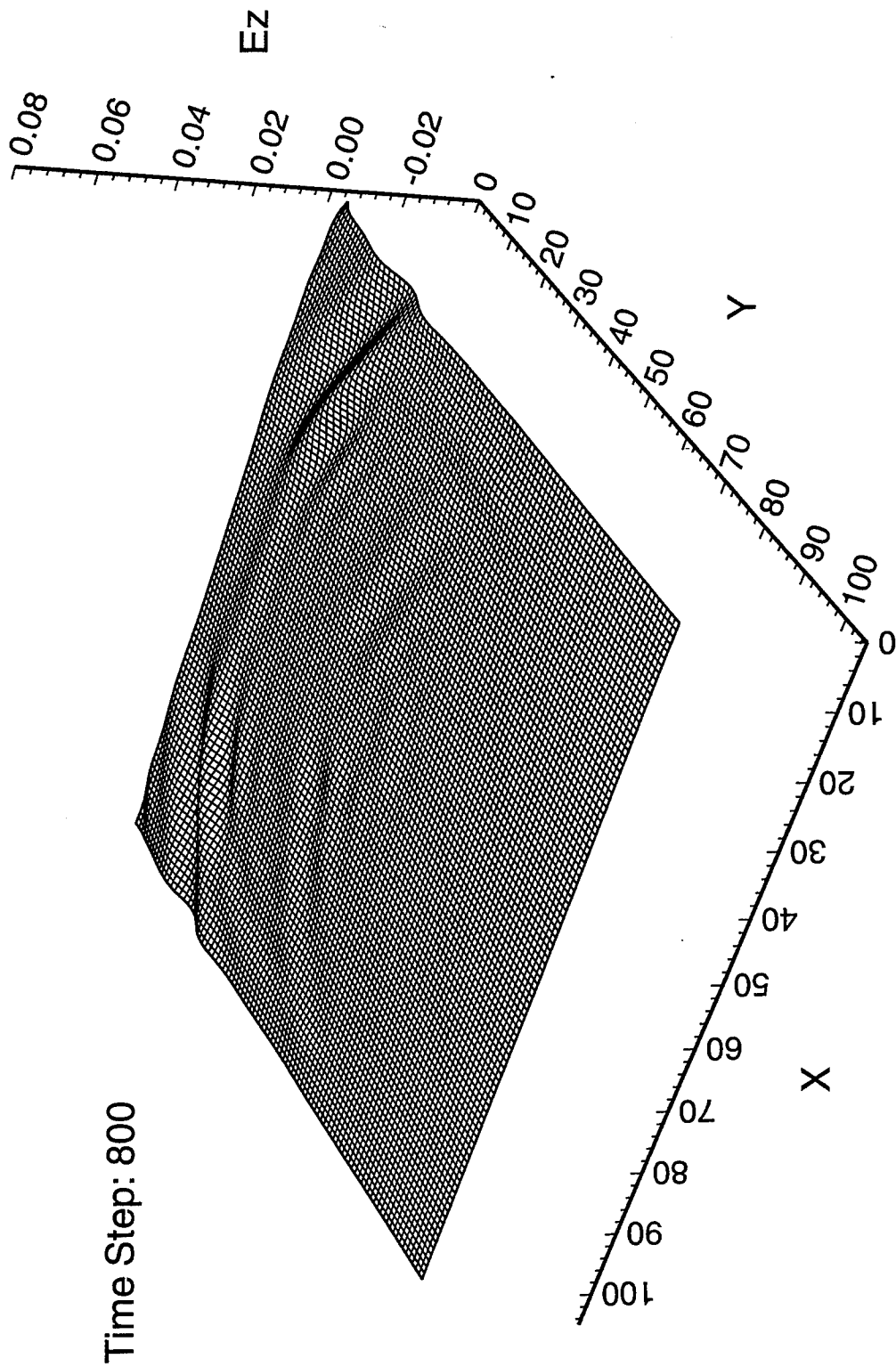
Figure 4. Distribution of electric field intensity (V/m) for one scatterer vs. X (5.0 x 10⁻³ m) and Y (5.0 x 10⁻³ m), time step - 800.

2-D Scattering of Two(2) Buried Rectangular Objects

Time Step:330

Figure 5. Distribution of electric field intensity (V/m) for two scatterers vs. X (5.0×10^{-3} m) and Y (5.0×10^{-3} m), time step - 330.

13
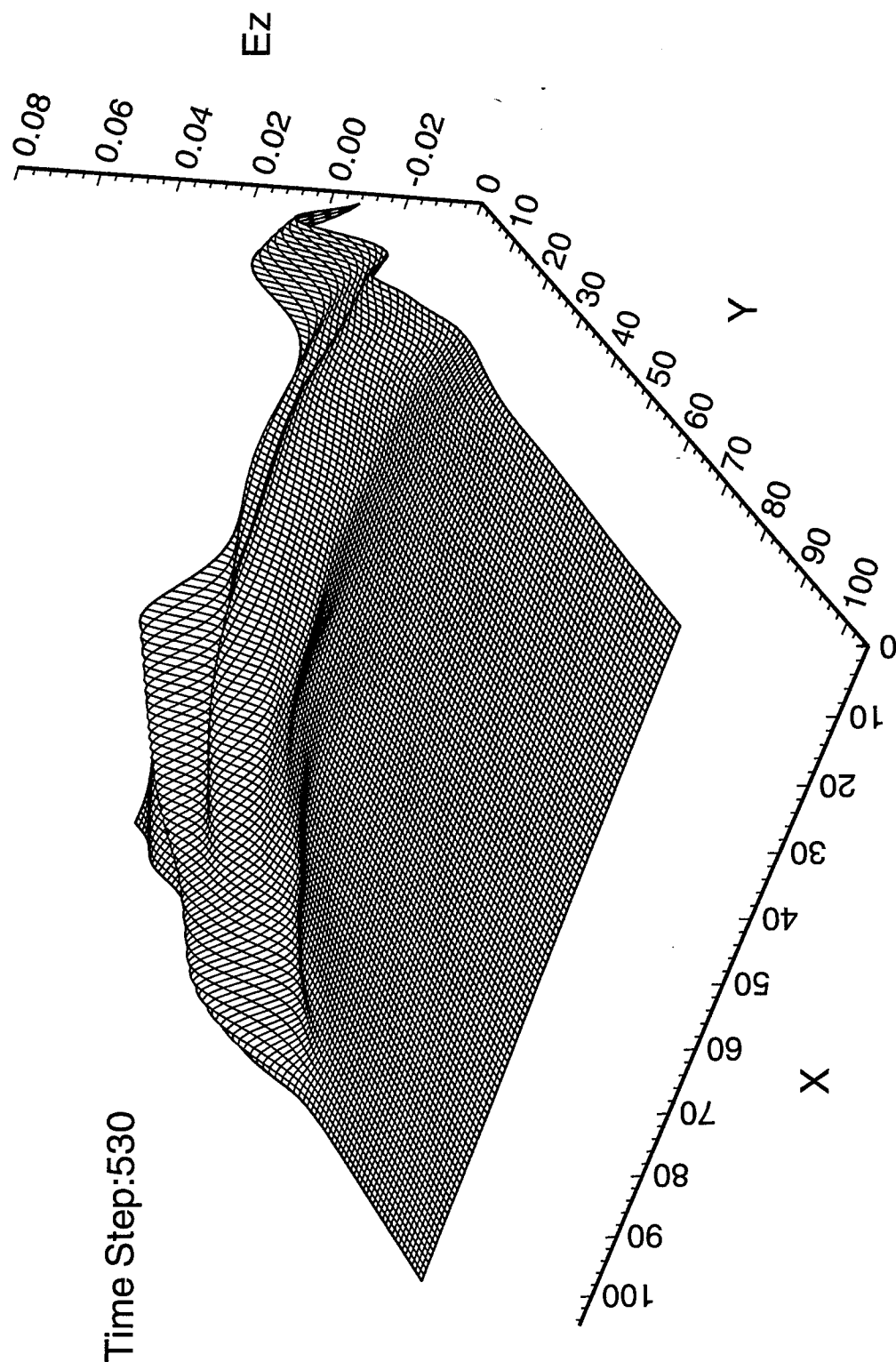
Figure 6. Distribution of electric field intensity (V/m) for two scatterers vs. X $(5.0 \times 10^{-3}$ m) and Y $(5.0 \times 10^{-3}$ m), time step - 530.

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2-D Scattering of Two(2) Buried Rectangular Objects

Ez

0.08
0.06
0.04
0.02
0.00
-0.02

Y

0 10 20 30 40 50 60 70 80 90 100

X

0 10 20 30 40 50 60 70 80 90 100
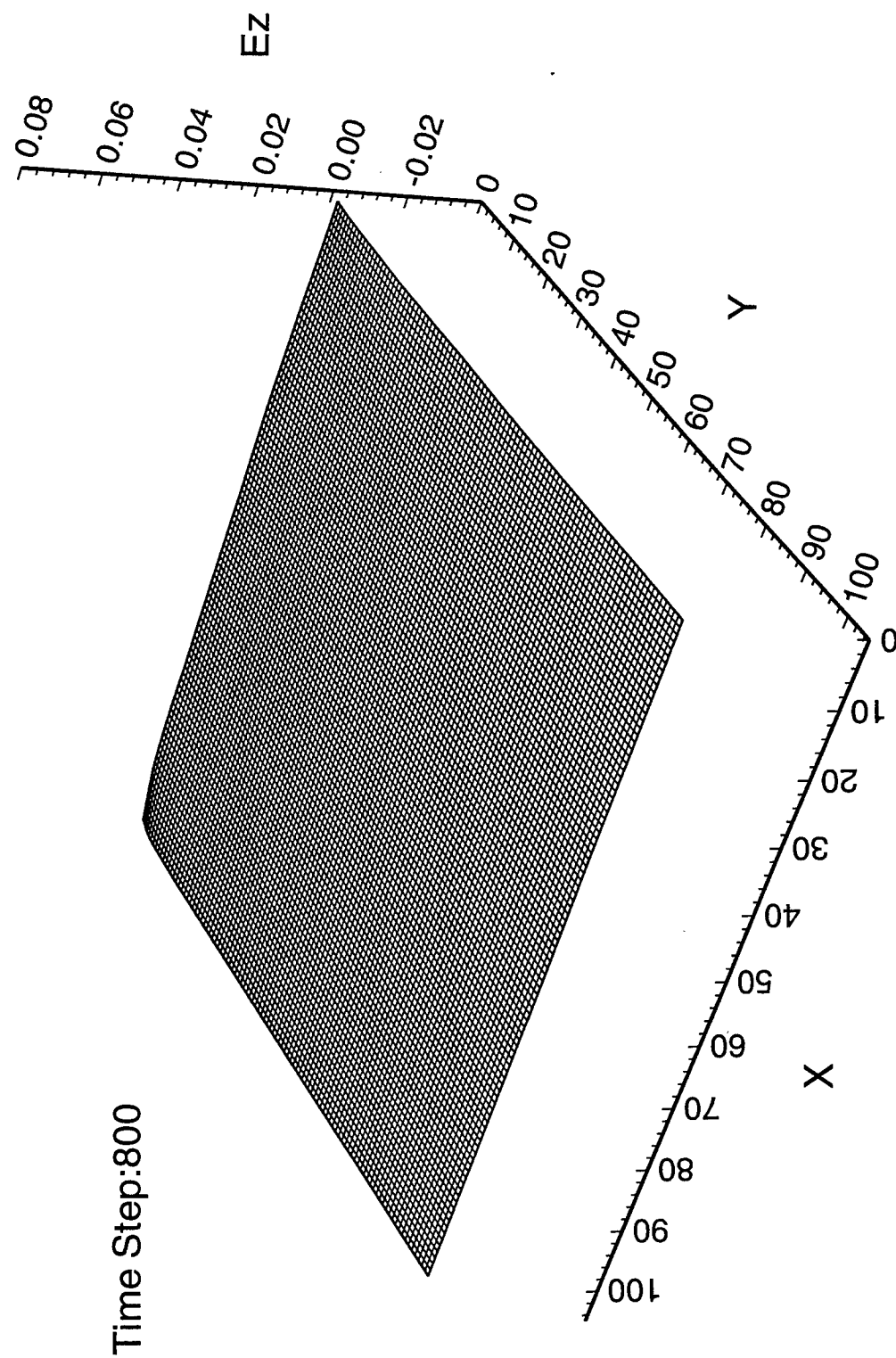
Time Step:800

Figure 7. Distribution of electric field intensity (V/m) for two scatterers vs. X (5.0×10^{-3} m) and Y (5.0×10^{-3} m), time step - 800.

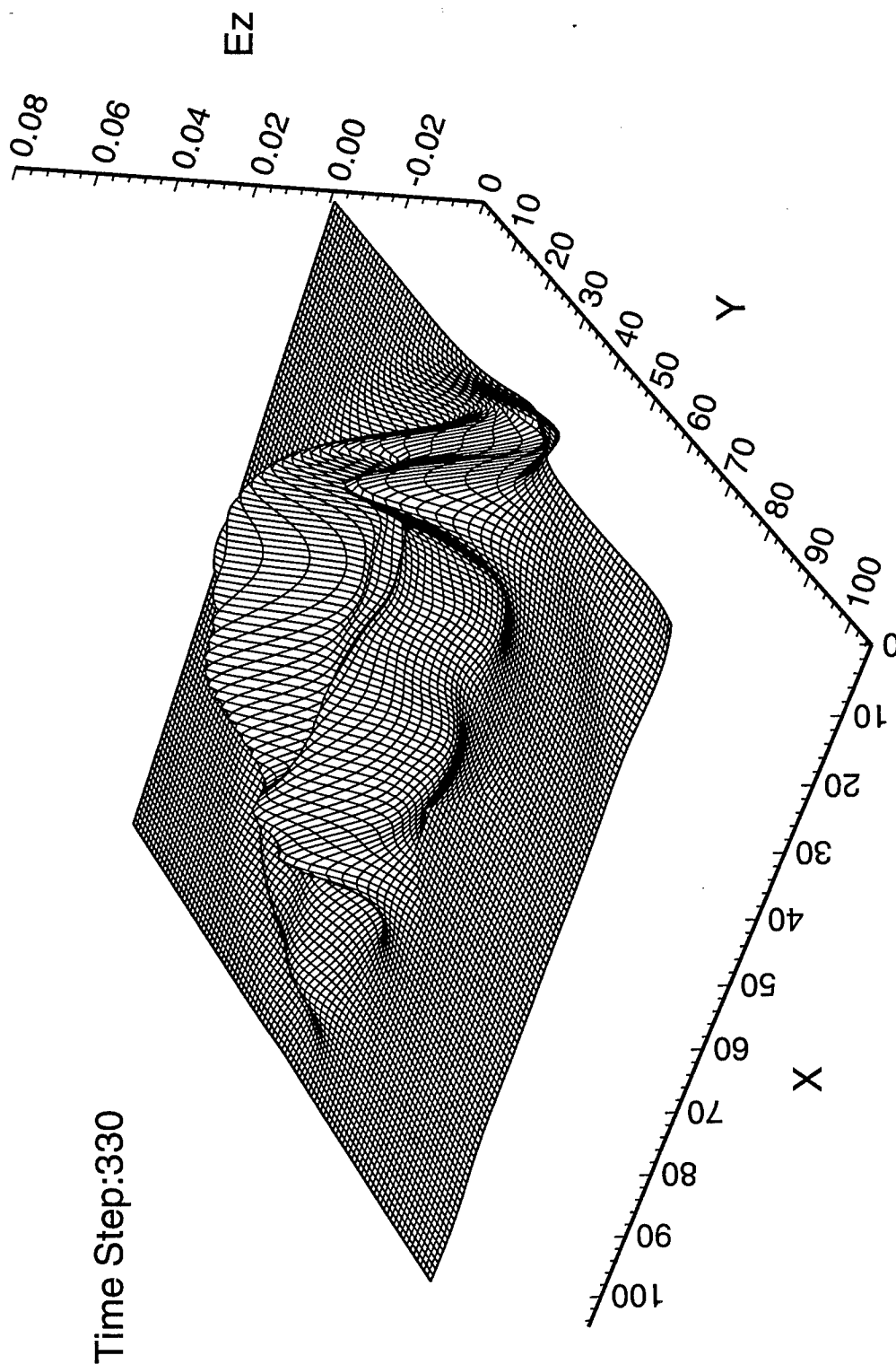2-D Scattering of Three(3) Buried Rectangular Objects

Ez
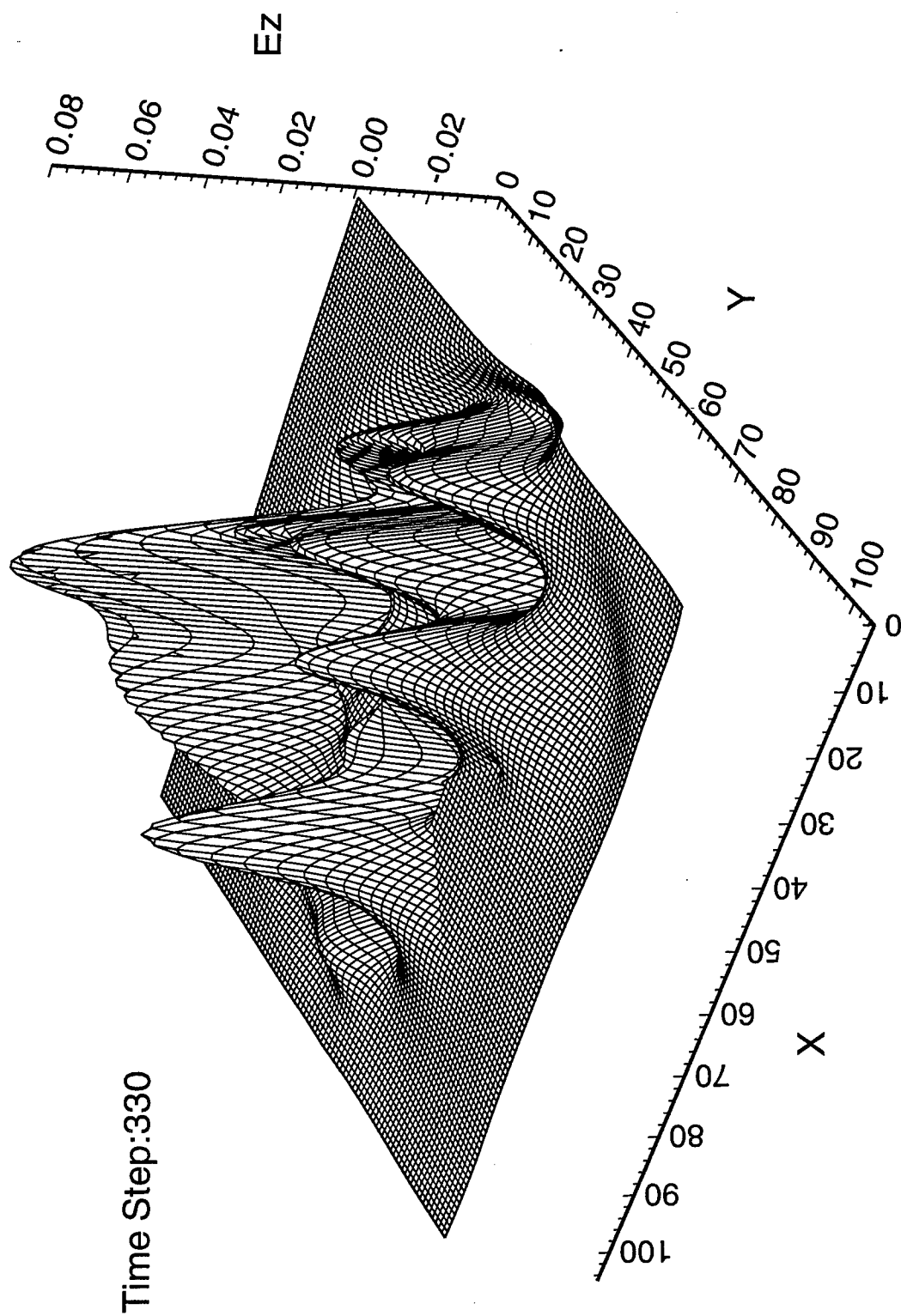
Time Step:330

Figure 8.   Distribution of electric intensity (V/m) for three scatterers vs. X (5.0 × 10^{-3} m) and Y (5.0 × 10^{-3} m), time-step - 330.
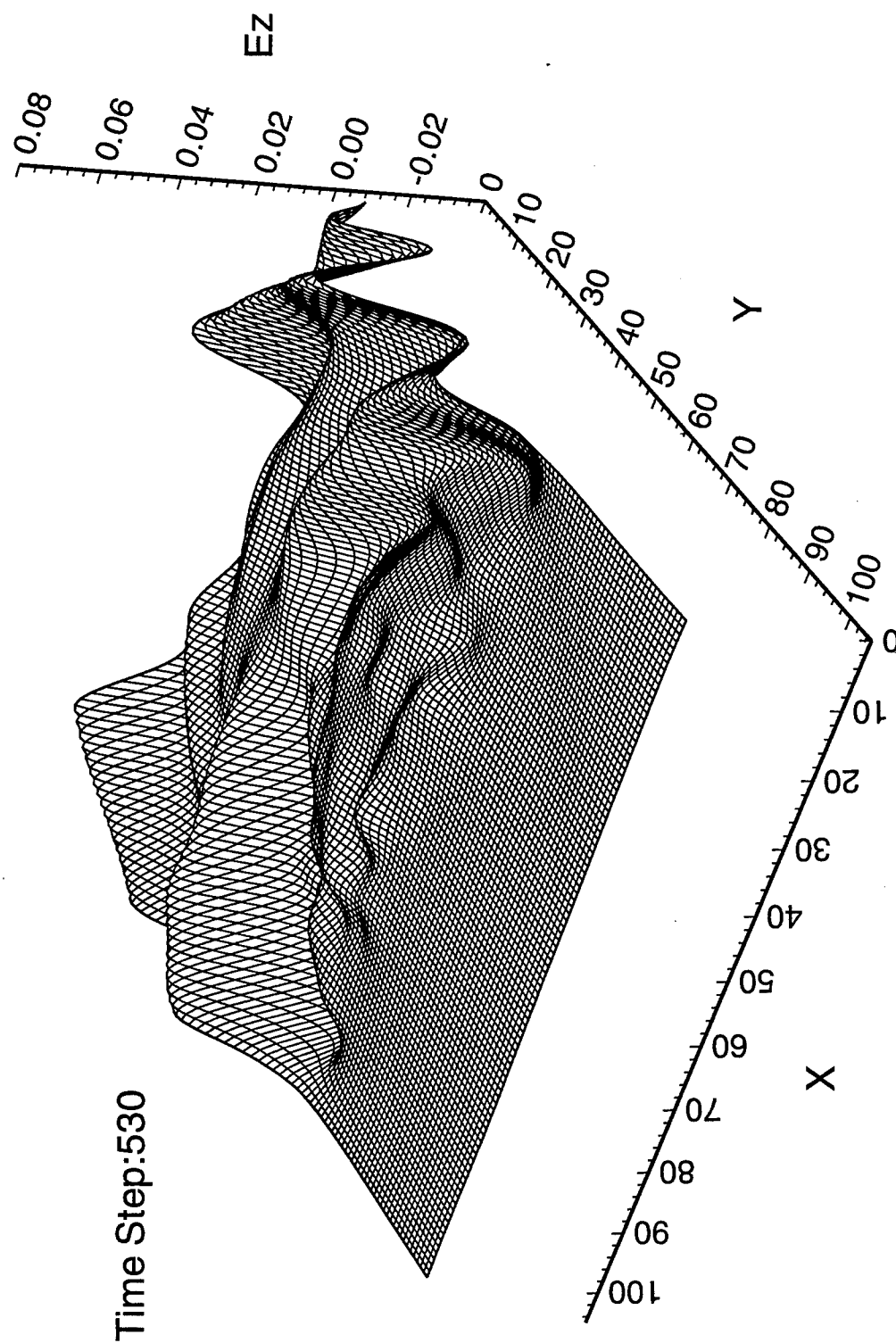
Figure 9. Distribution of electric intensity (V/m) for three scatterers vs. X (5.0×10^{-3} m) and Y (5.0×10^{-3} m), time step - 530.

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2-D Scattering of Three(3) Buried Rectangular Objects

Time Step:800

Ez

Y

X
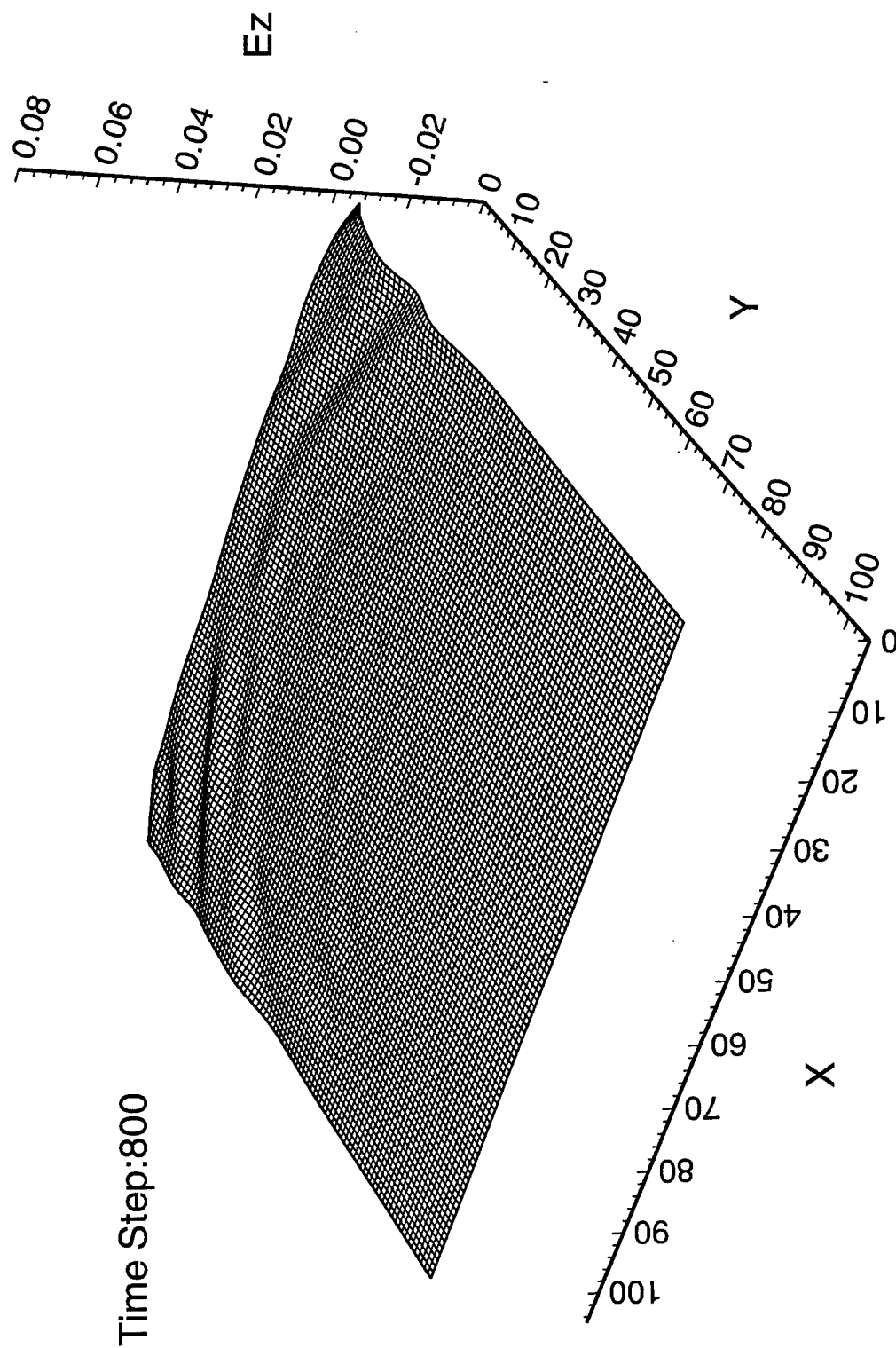
Figure 10.   Distribution of electric intensity (V/m) for three scatterers vs. X (5.0×10^{-3} m) and Y (5.0×10^{-3} m), time step - 800.

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simulated conditions as presented in this report, i.e., conductivity (s) for the air is 0, conductivity for the earth is 0.01, conductivity for the grass is 0.005, and conductivity for the mines are 0, 0.02, and 0.008; permeability (V • s/A • m) values ranged from 1 for air, 9 for earth, 5.5 for grass, and 2.3, 5.6, and 23.0 for the mines, respectively. The relationship between the scatterer shape and frequencies scattered is a very complex situation and is well beyond the scope of this work. In addition, an analogous program can be written for the transverse-electric (TE) case. Computation indicates that the difference of scattered signals between single and multiple scatterers are considerably obvious from the point of view of both time domain and frequency domain.

Furthermore, this work can also be extended to the case of 3-D EM scattering from single or multiple scatterers with ABC or non-ABC. We are currently investigating the 3-D FD-TD case of this same problem to run on a vector and parallel machine.

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